SECOND QUARTERLY PROGRESS REPORT ON SOLAR ORIENTING DEVICE FOR EXPANDABLE FLAT-PANEL ARRAY, 1 OCTOBER TO 31 DECEMBER 1961

GER-10553
Report No. 2

26 January 1962
Copy No. 4

Contract DA36-039-SC-88913

DA. Task No. 3A99-09-002-04
U. S. Army Signal Research
and Development Laboratory,
Fort Monmouth, New Jersey

GOODYEAR AIRCRAFT CORPORATION

AKRON 15, OHIO

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Prepared by
G. J. McKeel

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Signal Corps Technical Requirements No. SCL-7591
dated 27 October 1960
DA. Task No. 3A99-09-002-04

GOODYEAR AIRCRAFT CORPORATION

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25500

Object: Investigation of methods for orientation of expandable flat-panel solar arrays; eventual design and fabrication of two experimental models

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PART 1 - PURPOSE

The purpose of this contract is to initiate and perform investigations of various types and methods of orienting systems to determine their limits, suitability, or both, for use with an expandable flat-panel array of solar cells in ground applications. These investigations will lead to the design and fabrication of two experimental models - one capable of orienting a solar array of approximately 10 square feet, and the other of 20 square feet.

Figure 1 gives the work program broken down into tasks and shows the time allotted to each.

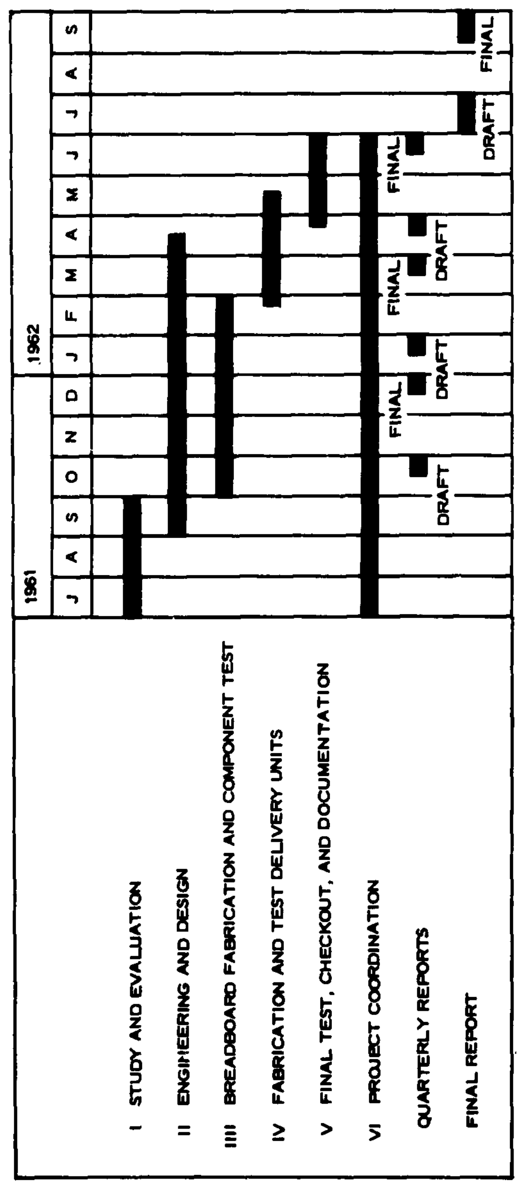

Figure 1 - Work Program for Orientation Device

PART 2 - ABSTRACT

This second quarterly report contains an extension of the orientation sensor analysis to the use of a shade for increasing sensitivity. A formula is found which can be used for determining the sensor pointing accuracy.

The effects of solar declination change on the total angular error of the array and the position for mounting the sun sensor are covered in this report. Curves of total angular error versus declination change for various values of the tracking drive error are presented. An example is outlined for calculating the possible period of unattended operation of the solar orienting device and its array for a particular set of initial conditions which contain a constant declination value.

The tracking rate for the array is examined to obtain an insight into some of the important parameters affecting its operation.

The requirements for automatic declination control applicable to the solar orienting device have been examined, and a feasible approach to the sensor is presented. A circuit diagram illustrates the additional hardware needed for two-axis automatic control. Sensor modification is discussed for the purpose of removing the dead zone which, under certain tracking conditions, can occur.

An elementary mount analysis is presented to obtain some idea of the effects of total height, leg length, and overturning forces on the array and its support structure. An expression is obtained involving these factors and the ratio of total weight to wind force.

Setting up the mount for outdoor conditions is discussed, relating some of the necessary equipment. The procedure is based on simple techniques which can be put into a standard operating procedure.

Experimental results gained from the breadboard model of the mount and drive unit are given, and the sun sensor accuracy is also obtained. Photographs of the breadboard mount and sun sensor are included.

PART 3 - PUBLICATIONS, LECTURES, REPORTS, AND CONFERENCES

A conference was held on 28 November 1961 at USASRDL, Ft. Monmouth, New Jersey, for discussion of the first quarterly report and the current progress. The progress reached by Hamilton Standard was requested during this meeting to determine the details which may significantly affect Goodyear Aircraft Corporation's (GAC's) mount and sensor design.

Dr. E. Kittl, Mr. G. Hunrath, Mr. S. Shapiro, Mr. R. Nichols, and Mr. A. Herchakowski attended this meeting as representatives from the Power Sources Division of USASRDL, and Mr. G. McKeel and Mr. L. Roberson represented GAC.

The preliminary draft of the first quarterly progress report was discussed. A few comments were made pertaining to technical errors. Recommendations were made to change the title page and abstract cards and to include a conference report of a previous meeting at USASRDL. It was stated that these changes would be incorporated prior to final publication.

Photographs and drawings were shown of the experimental breadboard model of the mount and drive unit. Dr. Kittl pointed out that the mount should be able to bring the expandable array into a horizontal position at some predetermined wind loading in order to prevent destruction of the entire unit.

Dr. Kittl inquired about GAC plans for the automatic control of the declination axis. It was pointed out that GAC is providing a manual control (or setting) about this axis, although a study will be made to determine the effect of a constant or locked declination setting and to determine the design

changes required to incorporate an automatic declination adjustment.

The question of the optimum speed for the drive motor was discussed; it appears that this speed would depend upon the time to achieve maximum power output required for a particular position of the solar array from the normal incident position.

It was stated that the expected output voltages of the array would be 6, 12, and 24 volts, and it was recommended that the drive motor be operated on 12 volts. The two different size panels will provide 50 and 100 watts. The estimated weight of each is 30 and 50 pounds.

A design drawing of the Hamilton Standard expandable array was shown. The drawing was not up-to-date although the weight and power figures were approximately correct. The size of the 100-watt panel is expected to be 25 square feet and the configuration nearly square. Hamilton Standard's array consists of modules of solar cells which can be packaged rather easily and assembled for the desired electrical characteristics. The problem of attachment of the expandable array to the mount will be considered at some later date.

In the afternoon, the discussion was primarily on the planned contents for the second quarterly report, as well as future program plans. It was stated that GAC plans to have the breadboard model of the mount, with a panel and a sensor attached, for demonstration of tracking during the month of January 1962. GAC will contact USASRDL to arrange for an actual indoor demonstration in January 1962. The breadboard model will be tested and evaluated to obtain the final design configuration.

A study of the optimum methods of actually setting up the mount and ensuring that it will operate with maximum efficiency will also be considered.

The investigation of problems relating to the terrain and methods of firmly anchoring the mount must also be considered for effective operation of this device. The method of leveling the mount on hillside sites and methods of anchoring to a rocky surface are just a few of the problems that must be considered.

It was considered that possibly only one mount is required and that an interchange of motors is all that may be needed for operating the mount with the larger sized array. Fine adjustment procedures were discussed; it was decided that further study of the procedures is necessary. The design of the legs must consider the stress produced by possible wind loading conditions that may exist under actual operation. It is apparent that wind tunnel testing is desired to provide a sufficient understanding of the actual forces that will be transmitted to the mount and its legs during tracking in high winds.

PART 4 - FACTUAL DATA

SECTION I - ORIENTATION SENSOR ANALYSIS AND PRELIMINARY DESIGN

The use of a shade to increase the sensor sensitivity at the null point was pointed out in the first quarterly progress report, GER-10393[a]. An equation will be developed to relate the sun's direction to the sensor direction by measurement of shadow length (X) which is produced on the sensor face by the sunshade of length (b).

Figure 2 shows the sun sensor at an angle of α degrees with the sun, an included angle of 2β, and a shade length of b. The length of the shadow on the face of the sensor is given by X and is determined by using the law of sines:

$$X = \frac{b \sin \alpha}{\sin (\beta - \alpha)}. \tag{1}$$

For X = 3/8 inch, b = 2-3/4 inches, and β = 45 degrees, Equation 1 can be solved for α and yields a value of about five degrees. A sun sensor having these dimensions will de-energize the micropositioner whenever the pointing error is equal to or less than five degrees in a plane as long as the shadow on the sensor face produced by the shade of length b does not exceed 3/8 inch ($X \leq 3/8$ inch).

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[a]GER-10393, First Quarterly Progress Report on Solar Orienting Device for Expandable Flat-Panel Array, 1 July to 30 September 1961. Goodyear Aircraft Corporation, Akron, Ohio, 4 October 1961.

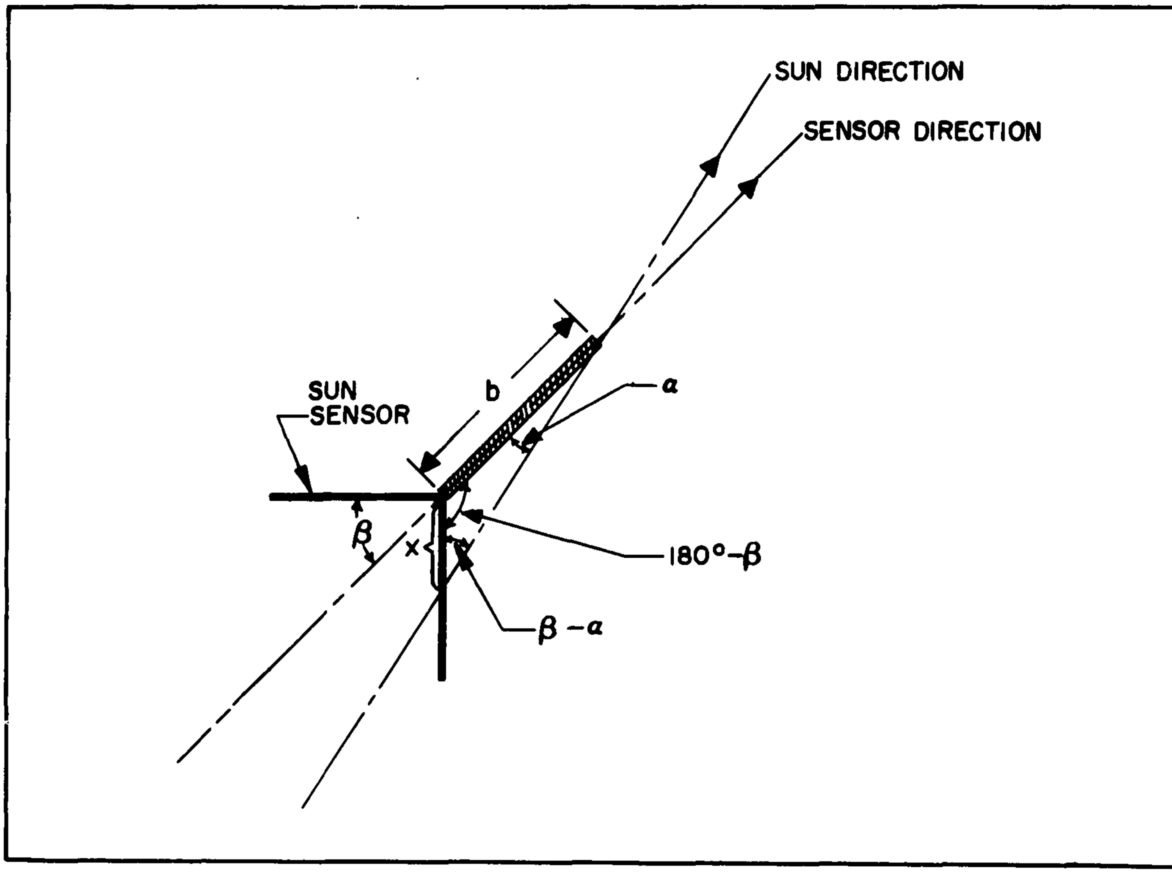

Figure 2 - Orientation Sensor with Shade

Assuming that the sensor is rotating at a uniform rate ($\dot{\alpha}$), the rate of motion of the shadow ($\dot{X}$) is given by

$$\dot{X} = \frac{b}{\sin\gamma}(\dot{\alpha} \cos \alpha - \dot{\gamma} \sin \alpha \cot \gamma) \tag{2}$$

where

$(\beta - \alpha)$ from Equation 1 $= \gamma$.

The time required to initiate the stopping of the array by de-energizing the micropositioner after starting from an initial setting of α (due to the sensitivity of the sensor) will be determined by the change in length (ΔX) of the shadow which will result in a sufficient decrease in sensor output to deactivate the micropositioner. The time (Δt) is given by

$$\Delta t = \frac{\Delta X \sin \gamma}{b \dot{\alpha} (\cos \alpha + \sin \alpha \cot \gamma)} \quad \text{since } \dot{\gamma} = -\dot{\alpha}. \qquad (3)$$

Using the 0.5 x 2 centimeter (Type 50520E9) solar cells made by International Rectifier Corporation, a sun sensor is being designed for use with the 10 and 20 square foot solar arrays. These cells have 9 percent efficiency, and the approximate current at 0.4 volt is 18 milliamperes. The higher output of the sun sensor will ensure its operation under reduced solar radiation intensity that will occur near the horizon.

Figure 3 illustrates this sensor and the four solar cells mounted on each face. The plate attached to the shade will enable higher accuracy from the sensor and is cut to length for ±6 degrees of declination error; i.e., the shadow on the cells which is produced by the plate is effective even with a declination of ±6 degrees of the sun (i.e., the sun is off the tracking plane of the sun sensor as much as 6 degrees).

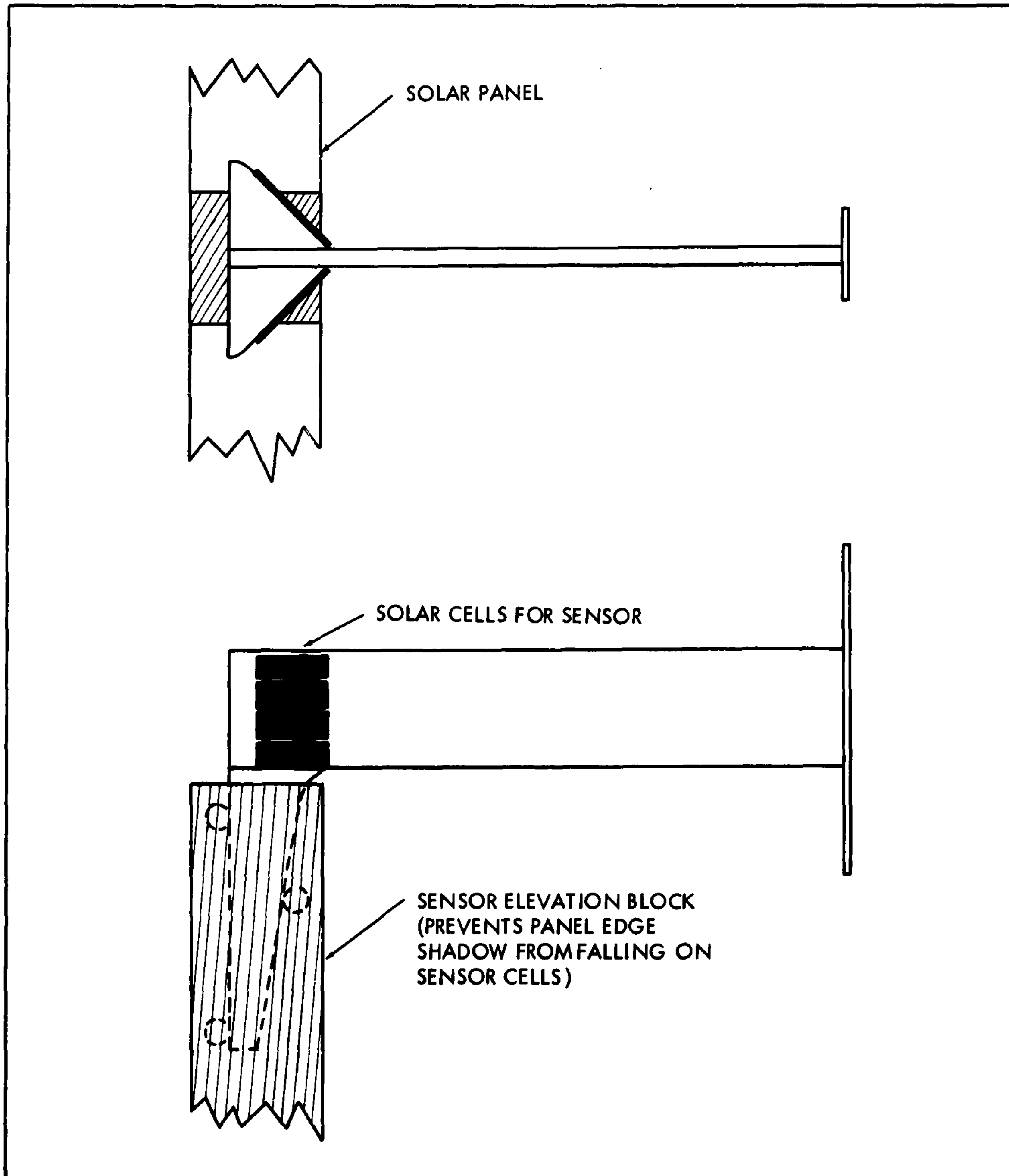

Figure 3 - Single Axis Sensor with 0.5 x 2 Centimeter Solar Cells

PART 4 - FACTUAL DATA

SECTION II - EFFECT OF SOLAR DECLINATION CHANGE ON THE TOTAL TRACKING ERROR AND SENSOR LOCATION

The ecliptic marks the plane of the earth's orbit, and the celestial equator indicates the plane of the terrestrial equator. It is known that these respective planes are inclined to each other by about 23-1/2 degrees. Because of the obliquity of the ecliptic, the sun's right ascension and declination will change as the sun moves eastward along the ecliptic. The variation in declination are seen as an annual north-south motion of the sun on the celestial sphere.

As the earth rotates daily, the sun will seem to describe diurnal circles from east to west parallel to the celestial equator as shown in Figure 4. The dividing line between the rising and setting of the sun is the observer's celestial meridian, and the sun's successive crossing of this celestial meridian is called upper transit. The hour circle through the apparent sun (A) has an hour angle of APZ west of the observer's (O) celestial meridian. The net effect to the sun's apparent eastward motion is the sum of the effects of obliquity and eccentricity.

For extended operation of a solar tracking device, the effect of declination change may be illustrated as shown in Figure 5. The declination change is represented by δ, which would occur after some definite period of operation, and ϕ is the hour angle error. The total allowable error is given by a and represents the amount of error that the normal to the solar array may be off from the sun's direction.

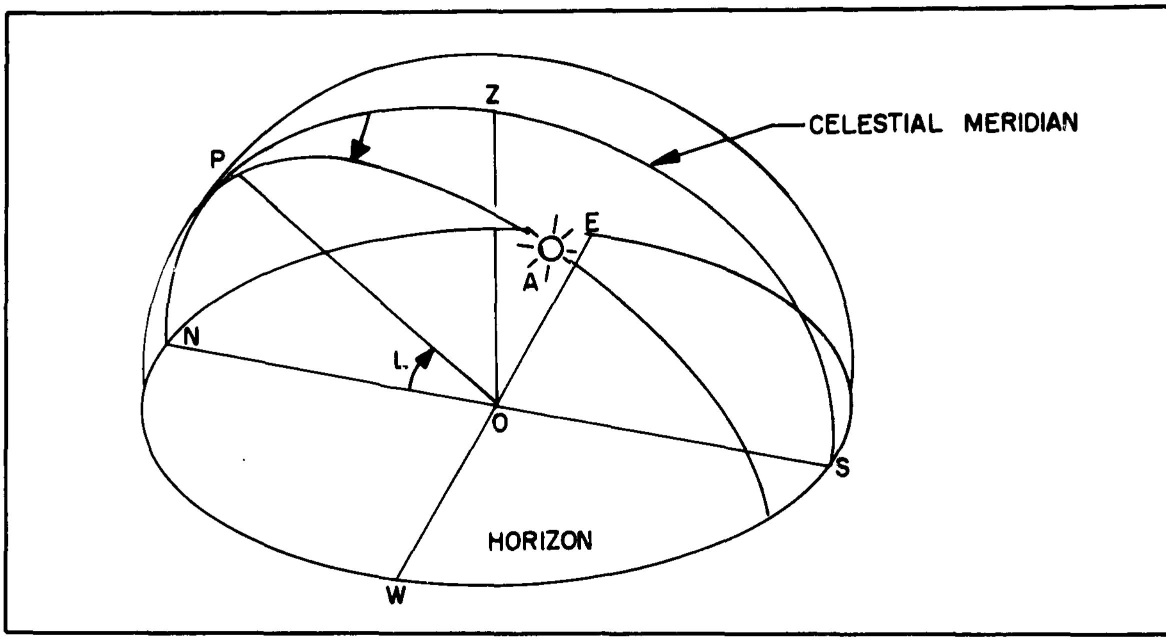

Figure 4 - Hour Circle through the Apparent Sun (A)

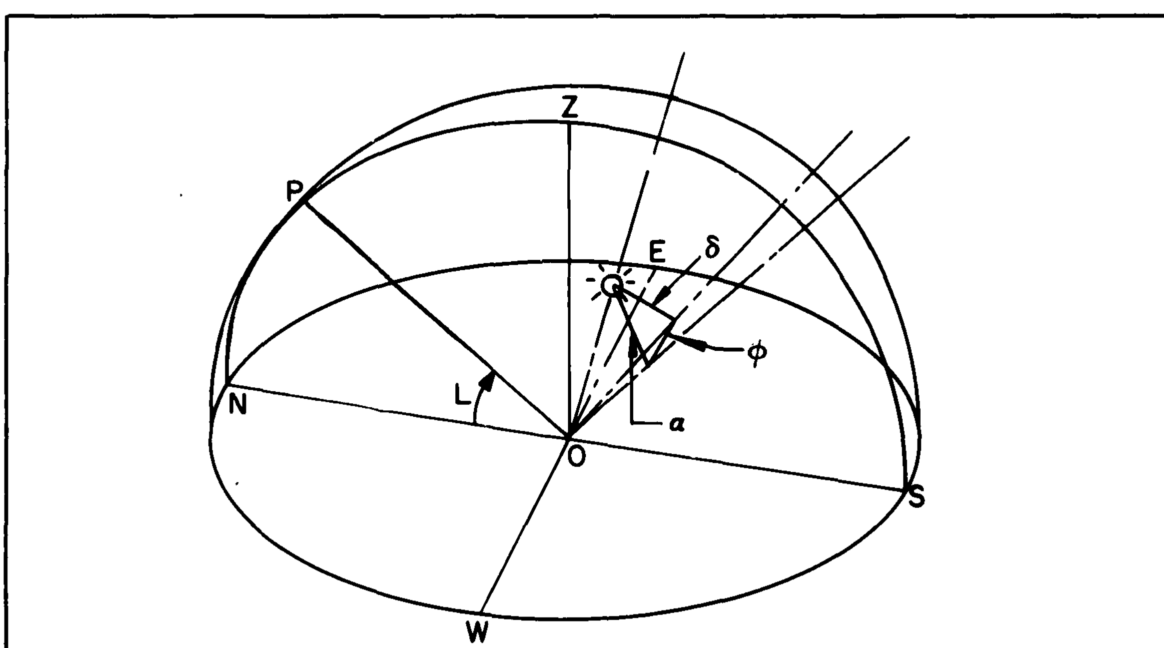

Figure 5 - Total Angular Error of Solar Array

Since the triangle in Figure 5 is a right spherical one,

$$\cos a = \cos \phi \cos \delta . \tag{4}$$

Figure 6 is a plot of Equation 4 and presents curves of total angular error of the expandable solar array from the sun's direction versus the sun's declination change. Separate curves are plotted for various values of the tracking drive error (0 to 10 degrees).

Table I[a] represents the total declination change of the sun during each month for the year 1962 at Greenwich.

TABLE I - MONTHLY DECLINATION CHANGES OF THE SUN (1962)

Month (1962)	Total Declination Change	Month (1962)	Total Declination Change	Month (1962)	Total Declination Change
January	5°35'14.4"	May	6°52'19.3"	September	11°27'45.0"
February	9°06'55.1"	June	1°05'59.0"	October	10°56'10.0"
March	12°07'12.1"	July	4°48'13.2"	November	7°14'58.3"
April	10°14'37.8"	August	9°21'11.1"	December	1°15'57.7"

It should be noted from Table I that the greatest change in declination occurs in March and September 1962. This is to be expected since the sun is at the

[a]Ephemeris of the Sun, Polaris, and Other Selected Stars for the Year 1962. 53rd Edition prepared by Nautical Almanac Office, United States Naval Observatory. United States Government Printing Office, Washington, 1961.

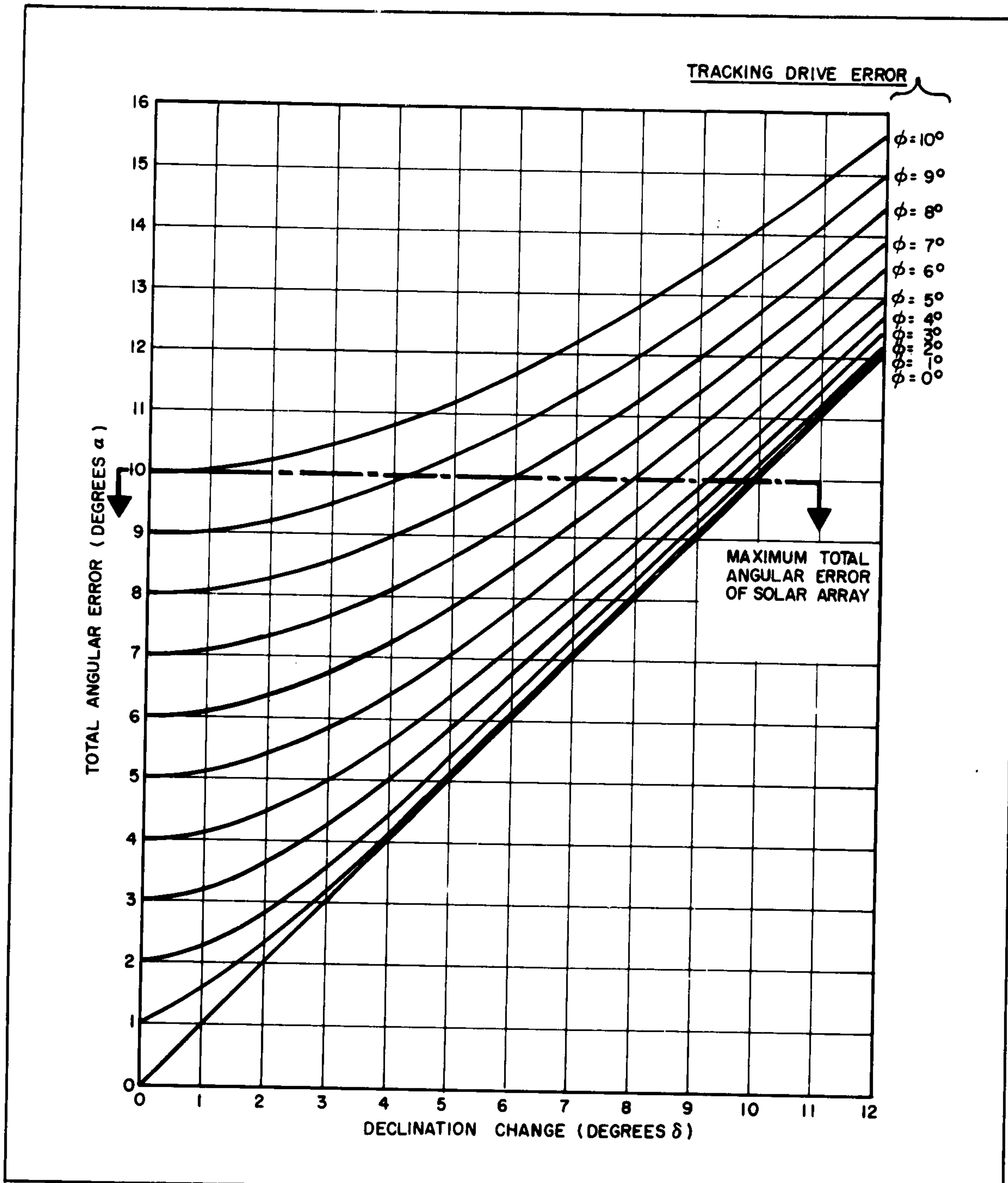

Figure 6 - Total Angular Error versus Declination Change for Various Values of Tracking Drive Error

vernal equinox and autumnal equinox during these months and the slope of the sun's declination versus sidereal time curve is maximum.

Since the sun's declination is changing with time and its value can be predicted accurately with the aid of the ephemeris, some mean value of the solar declination can be used for a constant setting. From Figure 6 a declination change of eight degrees can be tolerated with a tracking drive error of six degrees (total angular error of the array does not exceed ±10 degrees).

If it is assumed that the array is set up on 1 March 1962 (Greenwich time) when the sun is at a declination of S $7^{\circ}39'22.1''$ and the array is adjusted for a constant declination setting of $0^{\circ}0'0''$, this initial setup can be utilized through 10 April 1962 (a total of 42 days of unattended operation). The value of the sun's declination on this date is N $7^{\circ}52'22.6''$, and the solar panel has not exceeded the total allowable angular error of ±10 degrees.

When the solar array is rotating about an axis perpendicular to the ecliptic plane, there is no shadow produced by the edge of the array on the sun sensor. As the declination of the sun changes, it is possible to have the panel in the position shown in Figure 7.

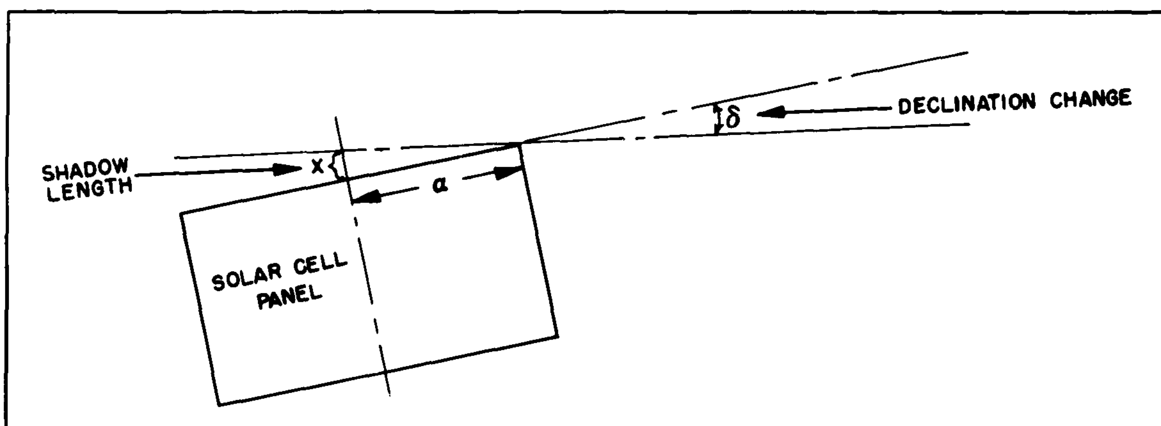

Figure 7 - Edge Shadow Due to Declination Change

With the sun sensor mounted at the center of the top edge of the array, base of the sensor should be about four inches above the upper edge of the array for the 25 square-foot size and 2-1/2 inches for the 10 square-foot size to prevent the shadow produced by the side of the array from falling on the solar cells of the sun sensor (declination change up to seven degrees).

PART 4 - FACTUAL DATA

SECTION III - TRACKING RATE ANALYSIS

The power required for the drive motor is directly related to the tracking rate that is used for the array. The higher the tracking rate the more power required for the drive motor. The power required for the d-c drive motor may be expressed as $P_m = K_m \dot{\alpha}$ where K_m is a constant term containing the torque and gear efficiency. $\dot{\alpha}$ is the tracking rate of the expandable array. The output of the array P_A may be expressed by $P_A = P_{max} \cos \psi$ where P_{max} is the maximum available power from the array at normal solar incidence and ψ is the angle between the vector normal to the surface of the array ($\bar{N}$) and the vector direction of the sun ($\bar{S}$). Figure 8 shows these vectors and their angular relationship in a plane at a given time (t). The initial conditions may be taken at $t = t_0$ where $\alpha = 0$ and $\theta = \psi = 180$ degrees.

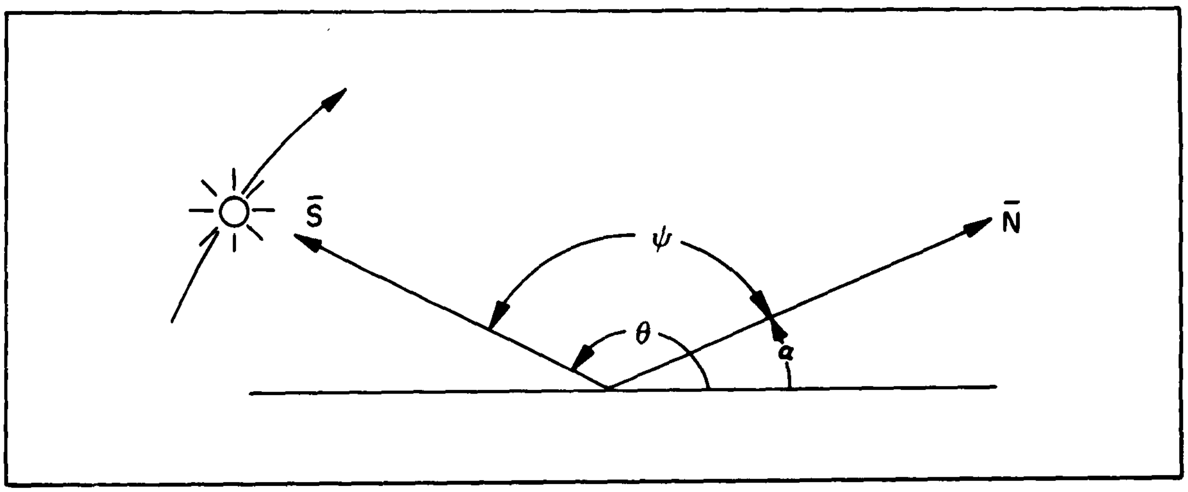

Figure 8 - Vector Diagram of Sun Direction and Normal to Array

Since $P_A = P_{max} \cos \psi$, the rate of change of P_A with time (t) is given by

$$\dot{P}_A = -P_{max}\, \dot{\psi} \sin \psi$$

and

$$\dot{\psi} = -(\dot{\theta} + \dot{\alpha}).$$

Therefore,

$$\dot{P}_A = P_{max}\, (\dot{\theta} + \dot{\alpha}) \sin \psi,$$

$$\frac{dP_A}{dt} = 0 \text{ at } \psi = 0,$$

and

$$\dot{\alpha} = \frac{\dot{P}_A}{P_{max} \sin \psi} - \dot{\theta}\,. \qquad (5)$$

The sun's apparent motion ($\dot{\theta}$) is known and has a value of 15 degrees/hour or 7.27×10^{-5} radians/second. The desired rate of change of P_A may be specified, and knowing the power in watts expected from the array at normal incidence, $\dot{\alpha}$ (the tracking rate) may be calculated for various values of ψ. As an example, assume that ψ has the value of 90 degrees, P_{max} is 50 watts, and the desired rate of change of P_A (array output driving toward maximum) is 0.5 watt/second. Putting these into the equation,

$$\dot{\alpha} = \frac{\dot{P}_A}{P_{max} \sin \psi} - \dot{\theta}$$

$$\dot{a} = \frac{0.5 \text{ watt/second}}{50 \text{ watts (1)}} - .0000727 \text{ radian/second}$$

$\dot{a}$ = 0.010 - 0.0000727 = 0.01 radian/second or 0.573 degree/second, the approximate tracking rate for the array under these assumed operating conditions. Since the power consumed by the d-c drive motor is given by $P_m = K_m \dot{a}$,

$$P_m = K_m \left(\frac{\dot{P}_A}{P_{max} \sin \psi} - \dot{\theta} \right)$$

and for

$$\frac{\dot{P}_A}{P_{max} \sin \psi} \gg \dot{\theta}$$

$$\frac{P_m}{\dot{P}_A} = \frac{K_m}{P_{max} \sin \psi} , \qquad (6)$$

time in seconds required for the array output to match the power requirements of the d-c drive motor.

The power required to drive the array for a particular value of tracking rate ($\dot{a}$) is nearly a direct function of the peak value of torque developed because of wind speeds. Some power requirements for the d-c drive motor were presented in the first quarterly report for a $\dot{a}$ of 1/4 rpm.

The ratio of tracking rate to the sun's apparent motion $\dot{a} / \dot{\theta}$ should be large enough to ensure a reasonable time to attain maximum power output from the

array starting from some initial off-set condition. Starting and running power requirements for the motor must be considered in view of the peak wind loads to enable the tracking rate to be established.

PART 4 - FACTUAL DATA

SECTION IV– REQUIREMENTS FOR AUTOMATIC DECLINATION CONTROL

The addition of an automatic declination control system to the existing solar orienting device would enable longer periods of unattended operation. Another advantage would be the capability of higher accuracy, with two-axis automatic control, over the single drive system. It can be noted from Figure 6 that, with a tracking drive error of ψ = 4 degrees and a declination error of 3 degrees, the total angular error of the array is 5 degrees. If a limit cycle of ±3 degree declination error is established for the control system, the operation rate for the month having the greatest declination change would be approximately four.

Since the present sun sensor is designed for single-axis operation, a modification would be required to sense the sun's declination change. A solid pyramid having a square base as shown in Figure 9 may be utilized for the two-axis sensor. Two of the faces ("A") contain solar cells for the hour angle drive, and the other two faces ("B") sense the declination change of the sun.

The shade, which was a vane in the previous sensor, will now take on the shape of a solid block and will be used for both pair of faces of the pyramid. The "A" faces of the pyramid will be connected as before to provide a nulling signal for the hour angle drive, and the "B" faces will be connected to provide a nulling signal for the automatic declination adjustment of the solar array.

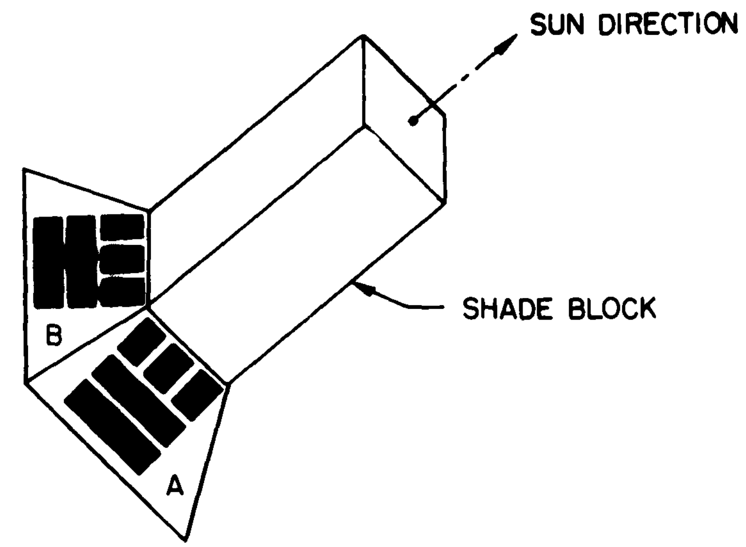

Figure 9 - Two-Axis Orientation Sensor

It was noted in the first quarterly report that a dead zone occurs in the sun sensor when it is pointing due west and the sun is rising in the east (i.e., the sun's radiation is falling on the back of the sensor). Rotation of the array and sensor is required to bring the faces of the pyramid into the sun's effective radiation. If two solar cells are mounted on the back of the square-based pyramid (each one capable of being connected in parallel across the cell group on the "A" faces), then when the sun's radiation impinges on the back cell that is connected across the appropriate cell group for rotation, the micropositioner will close and drive the array and sensor into the lock-on position. Figure 10 shows the sun sensor circuit for two-axis automatic control and the drive motor connections.

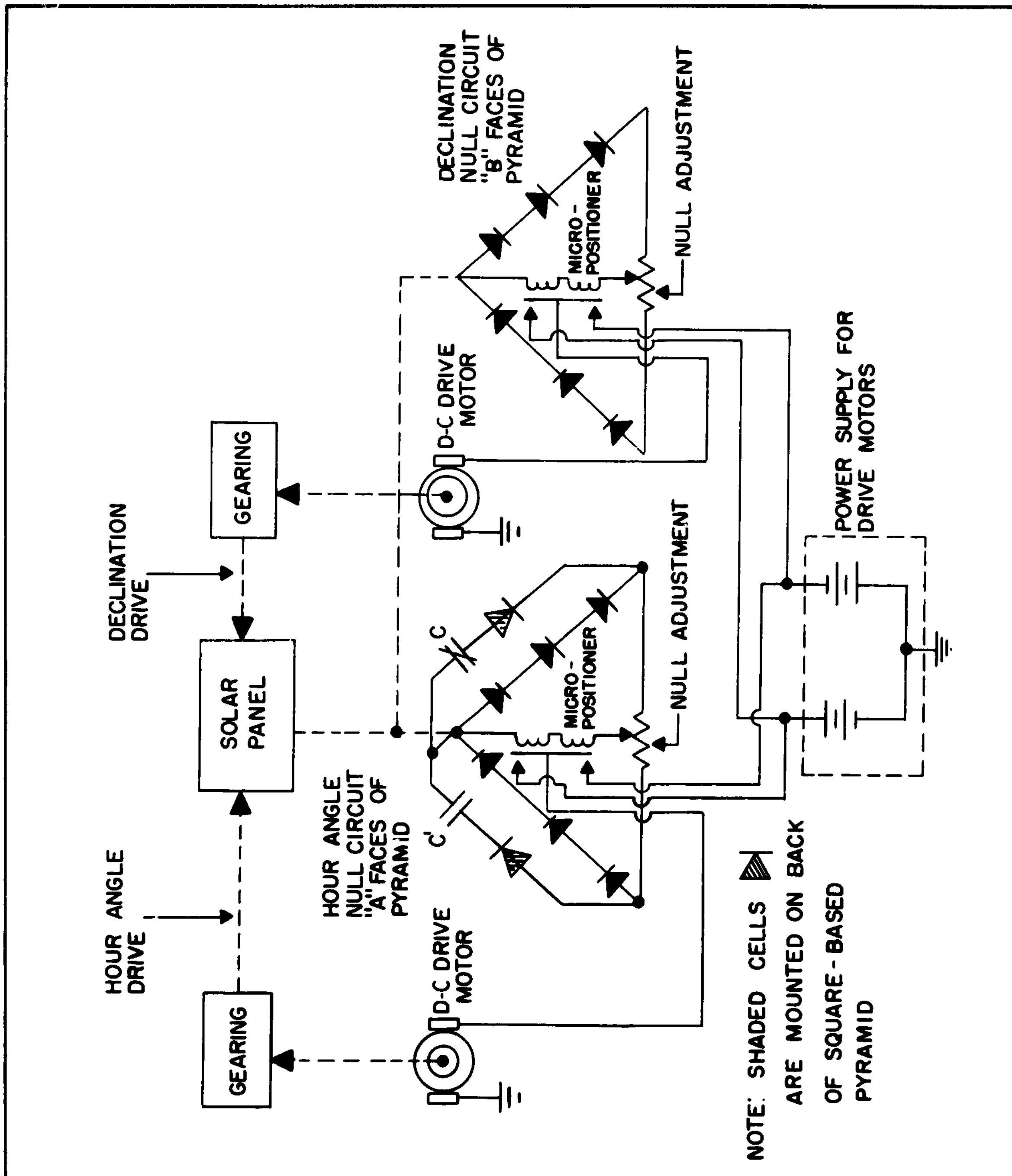

Figure 10 - Two-Axis Orientation Sensor Circuit Diagram

One of the contacts (C or C') shown in Figure 10 will be normally closed so that one of two back-mounted solar cells will be placed in parallel with one of the group of cells on the "A" faces to produce a signal for rotation of the array. The rotation will enable the sun sensor to come into the lock-on region so the solar cells on the "A" and "B" faces can resume operation. The circuit diagram of Figure 10 shows the additional equipment which consists of a micropositioner, revised sun sensor, extra d-c drive motor and gearing and the necessary mechanical linkage required for the two-axis automatic control of a solar array. Some additional power is needed for the declination drive, but since the duty cycle for this portion of the system is small the power drain will also be small.

PART 4 - FACTUAL DATA

SECTION V - MOUNT ANALYSIS

The effect of wind pressure on the array is to produce a force (F) and its corresponding moment (Fa), which may be considered to act about the axis through CD as shown in Figure 11. In the event that B, C, and D are not firmly held, the weight of the mount and array (W) may be considered to act along the axis AO to produce the countermoment (Wb). Setting these two

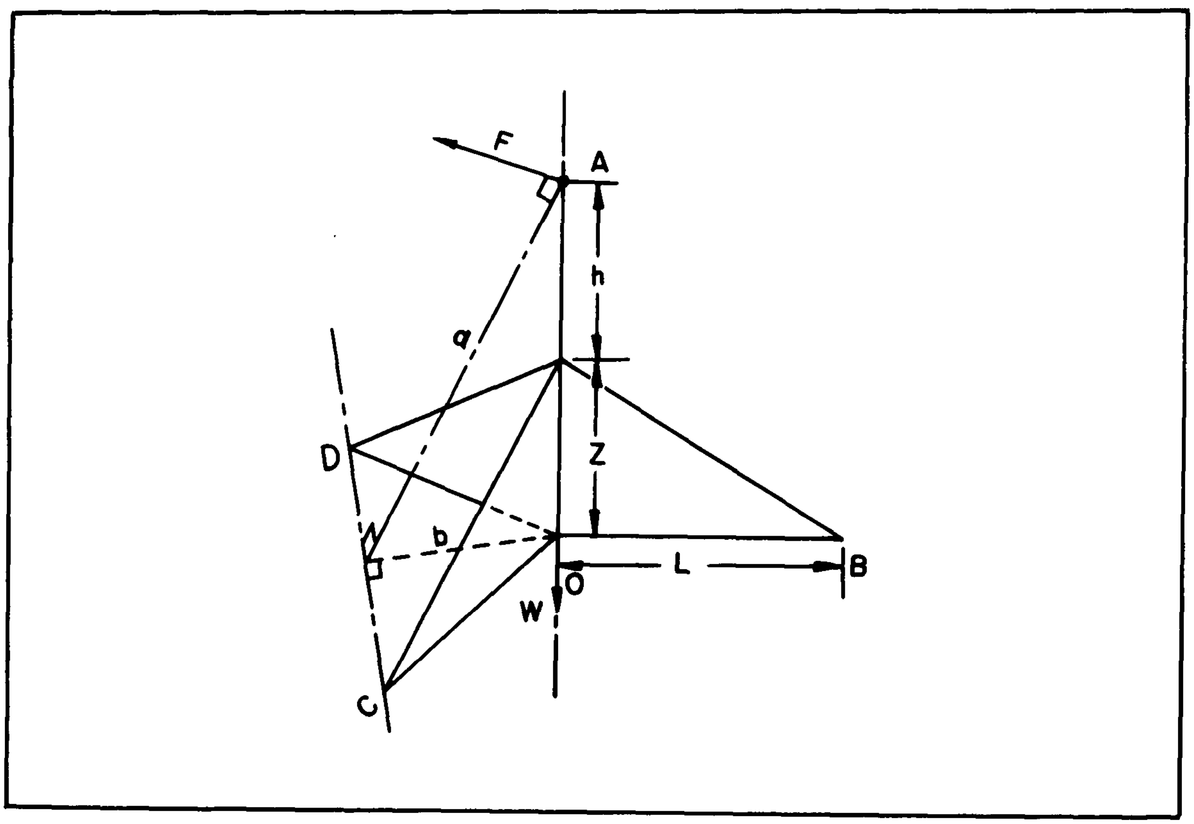

Figure 11 - Diagram of Resultant Wind Moment on Mount

moment equations equal to each other, the overturning force is found to be

$$F = \frac{Wb}{a} . \tag{7}$$

Assuming the array to be attached at the point (A), a distance (h) must be allotted to avoid interference from the legs. The length of each leg is L; the legs may be considered to be spaced 120 degrees apart. Therefore, b = L cos 60^{o} = L/2, and Equation 7 may be written as

$$a = \frac{WL}{F2} .$$

Since

$$a = \sqrt{b^2 + (Z+h)^2},$$

$$\frac{L^2}{4} + (Z+h)^2 = \left(\frac{W}{F}\right)^2 \frac{L^2}{4}$$

and

$$Z + h = \frac{L}{2}\sqrt{\left(\frac{W}{F}\right)^2 - 1} . \tag{8}$$

If the total weight to wind force ratio (W/F) has a value of 2, equation (8) reduces to

$$Z + h = L\frac{\sqrt{3}}{2} \text{ or } L = \frac{2(Z+h)}{\sqrt{3}} .$$

Knowing the value of (Z + h), the length of the legs (L) may be determined approximately for the assumed weight to wind force ratio of 2. Considering a 25 square-foot solar array (5 feet on a side) and using one half the diagonal distance of the array for h and a Z value of 1.5 feet, the length L is 5.83 feet. For the 10 square-foot array with a Z of 1 foot, the length L is 3.75 feet.

To effect a greater resistance to overturning and to increase the static stability of the mount and its array, consideration should be given to the latitude regions of operation. A restriction to certain latitudes of operation may permit a decrease in the length (h) and a corresponding lower center of gravity.

The regions within 23-1/2 degrees latitude of the earth's equator are the tropic zones and are characterized by the fact that within them the sun will appear at the zenith at least once a year. A mount designed to operate specifically within this region would require its polar axis to have an elevation variation of 0 to 23-1/2 degrees. The value of h in this case for a 25 square-foot array would be about 2.73 feet in comparison to 3.54 feet in the first approach. The center of gravity could be lowered by approximately 9.73 inches if it is restricted to the latitude limits of 0 to 23-1/2 degrees north or south.

The arctic zones are within 23-1/2 degrees of the poles north of latitude 66-1/2 degrees north and south of 66-1/2 degrees south. The sun shines for a full 24 hours at least one day a year in these regions. The mount designed for the arctic zones should be able to accomplish 360 degrees of rotation, and its polar axis would require an elevation setting of 66-1/2 to 90 degrees. The value of h in this case for the 25 square-foot array would be 2.5 to 2.73 feet and would reduce the height of the center of gravity significantly.

The areas between the tropic and arctic zones are the temperate zones, and the mount designed for these regions would have a polar axis elevation varied from 23-1/2 to 66-1/2 degrees. With a polar axis elevation of 45 degrees the value of h would have to be about one half the diagonal distance across the array or 3.54 feet to permit rotation of the array without interference from the legs at their upper hub attachment points. In the temperate zones the mount design should use the higher value of h; in the tropic and arctic zones a lower value can be used, and different mount designs should be considered.

In place of the tripod-type of mounting for the solar array, which has neither the static stability or the resistance to wind moments, a mount built in accordance with Figure 11 would be better suited for the actual outdoor operating conditions. Figure 12 illustrates this type of mount and the obvious advantage of the leg arrangement to permit a lower array mounting and center of gravity. The central tube and leg attachment will provide greater strength and torsional stability.

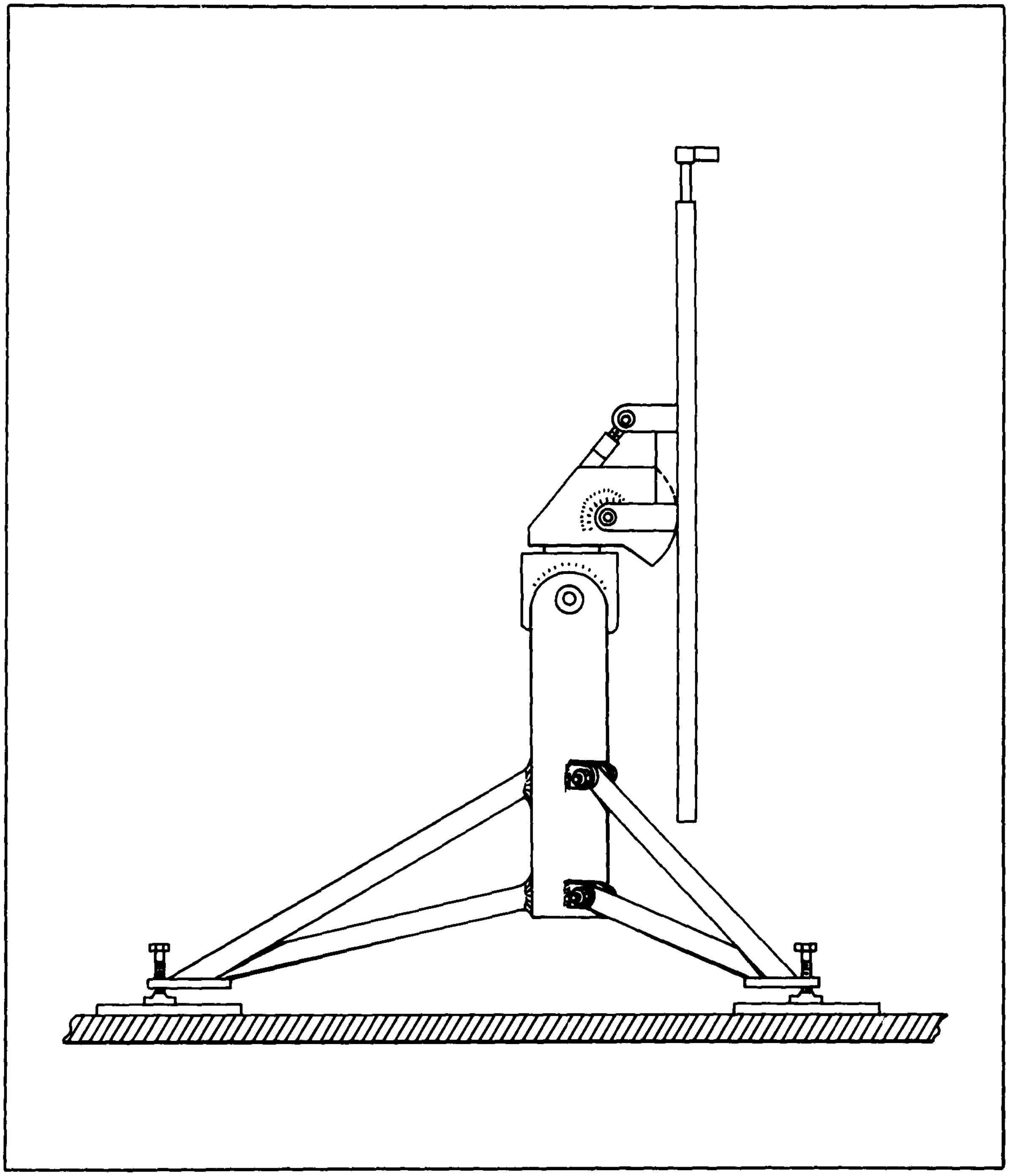

Figure 12 - Mount Configuration

PART 4 - FACTUAL DATA

SECTION VI - SETTING UP THE SOLAR TRACKING ARRAY

To establish the correct initial operating conditions for a solar tracking array a setup procedure must be studied and formulated. The proposed method described in this section is not necessarily an optimum, but it will provide some basis for further considerations.

The equipment that should be an integral part of the mount is a circular level (bubble level), possibly a compass, a latitude arc, and a declination arc. The solar array will rotate about the polar axis with a constant declination setting. The altitude of the polar axis is equal to the latitude of the observer, and a map of the area may be used to furnish latitude information.

The mount may be oriented in a north-south direction with the aid of a compass and then leveled with the circular bubble level. The array may be set parallel to the earth's axis by tilting and then clamping it with the visual aid of the latitude arc. The correct declination setting for the array may be obtained from an ephemeris and the knowledge of the initial tracking date. Since the values of declination in the ephemeris are given at Greenwich apparent noon, the local observer's time must be referenced to Greenwich time.

Figure 13 illustrates this procedure for setting up the solar tracking mount. The errors that are inherent in this procedure are due to the compass, bubble level, latitude arc, and the declination setting. The error associated with the circular bubble level will be on the order of 15 minutes of arc, and the latitude and declination arcs located on the mount will have an error of

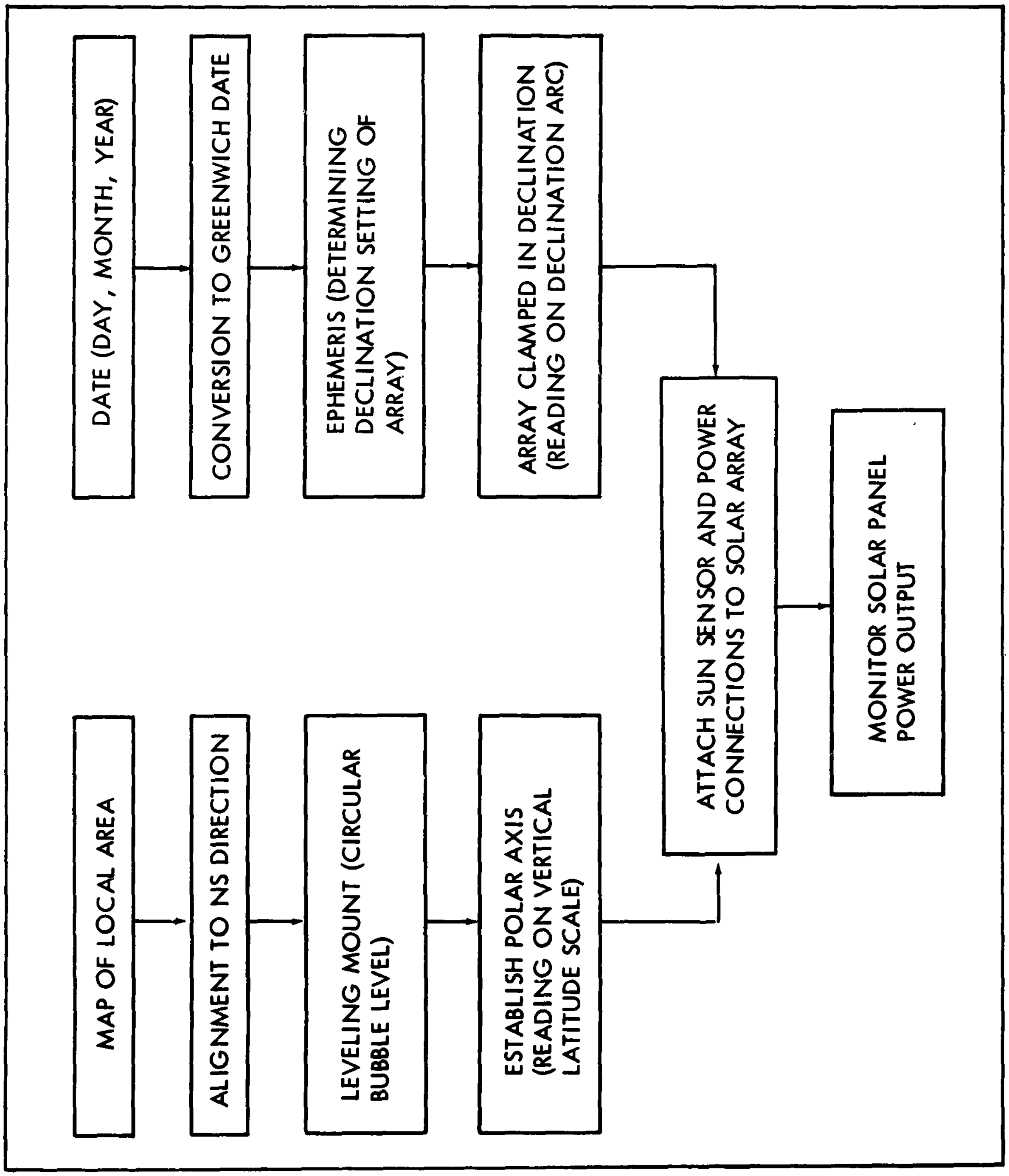

Figure 13 - Procedure for Setting Up the Solar Tracking Mount

10 to 15 minutes. The compass will be subjected to errors in magnetic variation and deviation. The variation is given on charts for the year in which they were published, and a statement of the annual change is given so that the variation to date can be computed.

A deviation table may be prepared for the compass, and the use of a map would provide more accurate alignment to the north-south direction. This method of setting up the mount can be done in the absence of solar radiation, but monitoring should be done to insure accurate north-south alignment.

After the mount has been set parallel to the polar axis and the declination setting has been made, the determination of the north-south direction may also be accomplished by rotating the array an appropriate number of degrees to bring the normal to its surface parallel to the direction of the sun. The number of degrees for rotation of the array may be found by multiplying the hours before or after local apparent noon by 15. Now, with the tracking circuit off, the mount and array may be rotated in either direction about the zenith to yield a drop in the panel output. The peak power point should occur when the mount is in alignment with the north-south direction.

PART 4 - FACTUAL DATA

SECTION VII - EXPERIMENTAL RESULTS

In accordance with the program for this period, a breadboard model of the mount was constructed of aluminum tubing and a drive head was fabricated to hold a simulated solar array. Figure 14 shows the mount and the drive head with rectangular bracket for mounting the solar array.

The tripod-type legs are attached to the drive head by two 1/2-inch nuts and compression washers to permit rotation of the drive head unit. This enables adjustment to the polar axis (which is through the drive head unit) to conform with the latitude of the operating site.

The declination adjustment on this breadboard model is manual and consists of a knurled aluminum handle threaded at both ends (left-hand and right-hand threads) and attached at the upper end of the mounting bracket and the drive platform. The other end of the array mounting bracket is pivoted at the drive platform, which is directly attached to the output gear. Rotation of the knurled aluminum handle, clockwise or counterclockwise, permits a manual declination setting (plus or minus).

A Barber-Colman motor-gearhead combination, Part No. BYLM 43312-2, with the following rating was used to provide the drive power for the array:

Rated voltage - 26 volts
Torque - 10 pound-inches
RPM - 14
Duty - continuous
Current - 0.40 amperes

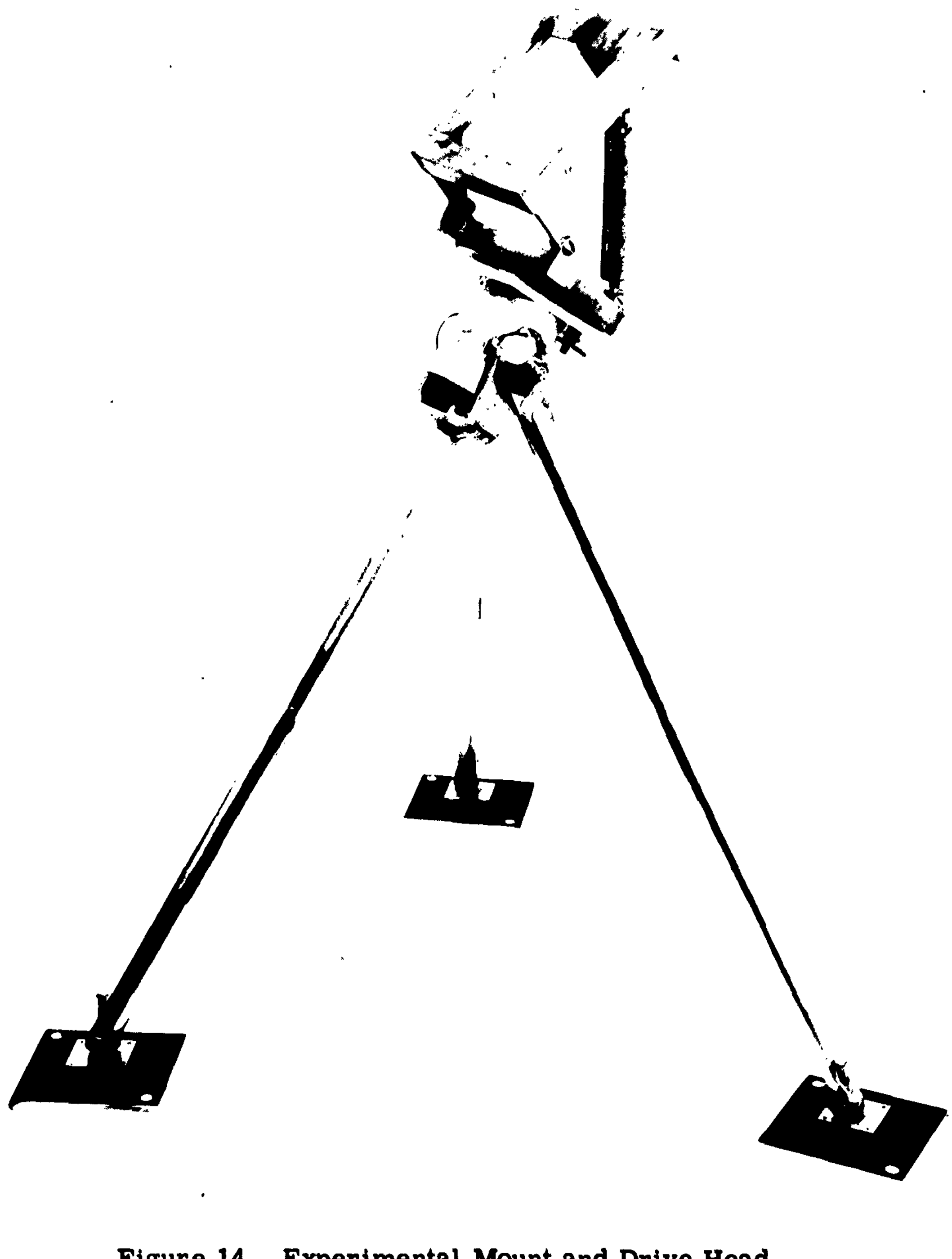

Figure 14 - Experimental Mount and Drive Head

The final gear combination in the drive head had a 73 to 1 gear ratio, so the final torque output to the array was 730 pound-inches or 60.83 pound-feet. The torque versus angle of attack curves (20 square-foot array) presented in the first quarterly report indicated that a torque of approximately 60 pound-feet may be produced by a wind speed of 40 mph.

It should be noted that the model shown and described in Figure 14 was built with a minimum of labor and cost for demonstrating the proposed techniques and testing. It is fully understood that the leg arrangement, feet, open gearing, static and torsional stability are not suitable for long periods of field-type operation.

Figure 15 shows the mount with a 1/2 inch BONDOLITE* panel (9 square feet) attached and with the sun sensor located at the center of the upper edge.

The sensor sensitivity curves presented in the first quarterly report indicate that higher sensitivity could be obtained from the sun sensor by using a smaller included angle at the apex of the sensor. A model of the sensor was fabricated with a 20-degree included angle. A larger angular lock-on range was obtained with this form of the sensor, but the available power near null was insufficient for the desired accuracy. The original design (90-degree included angle) of the sensor was fabricated with a longer sun shade according to the equation developed in Section I. Figure 16 shows this model with the 2-3/4 inch shade, which was utilized in the outdoor test on 26 December 1961.

The breadboard model of the mount and array shown in Figure 15 was adjusted for a latitude of 41 degrees and declination of -10 degrees on 26 December 1961 before the actual outdoor test. The declination of the sun for this date is about -23 degrees. A 45-volt, center-tapped "B" battery

* TM, GAC, Akron, Ohio

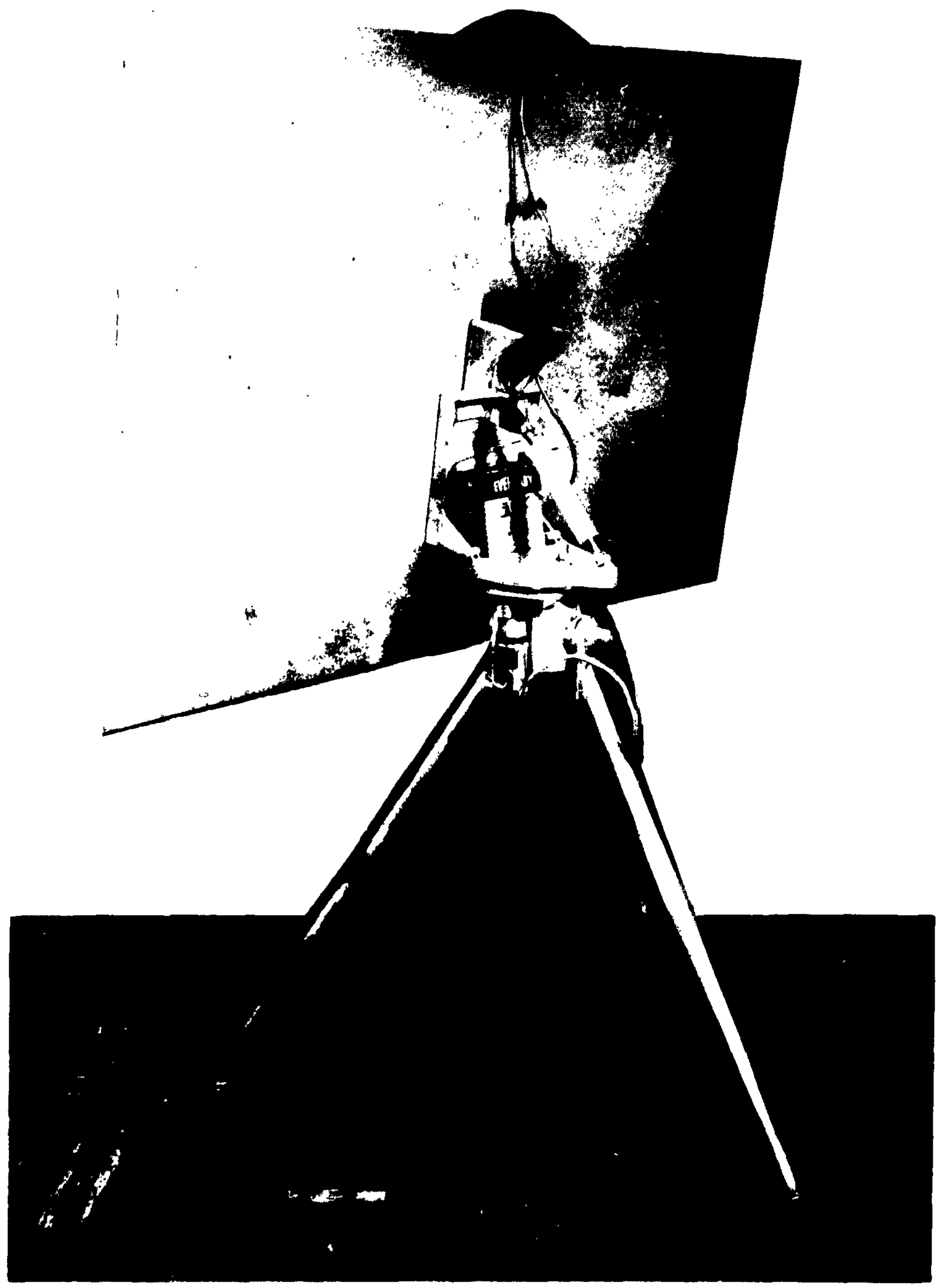

Figure 15 - Experimental Breadboard Model with Simulated Array

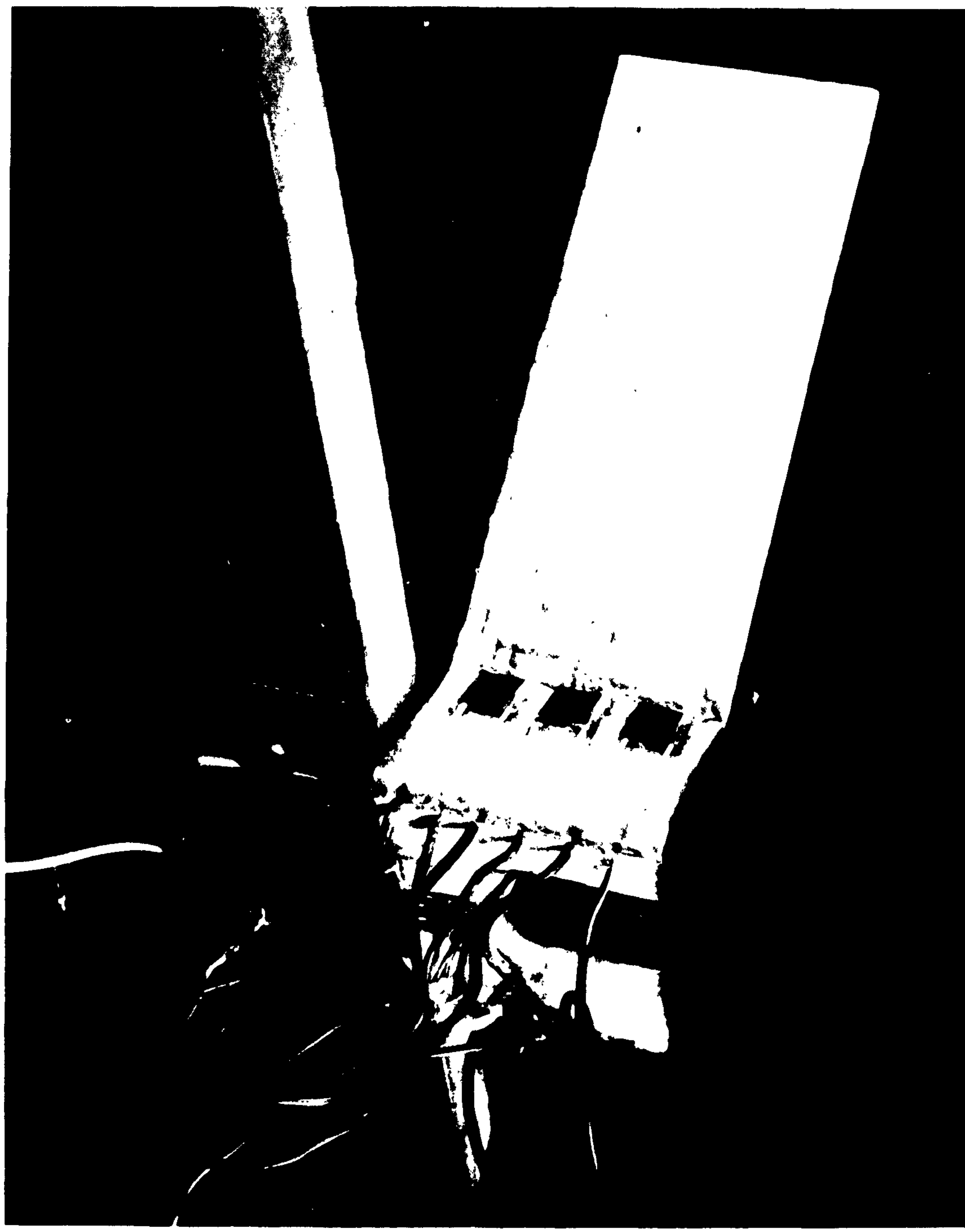

Figure 16 - Orientation Sensor with 2-3/4 Inch Shade

(EVEREADY No. 762-S) was used to supply power to the D-C drive motor.

Figure 17 illustrates the sensor circuit utilizing the 45-volt center-tapped "B" battery and Barber-Colman Micropositioner (Type AYLZ 4537S). This relay had a pull-in current of 0.5 to 0.7 milliamperes.

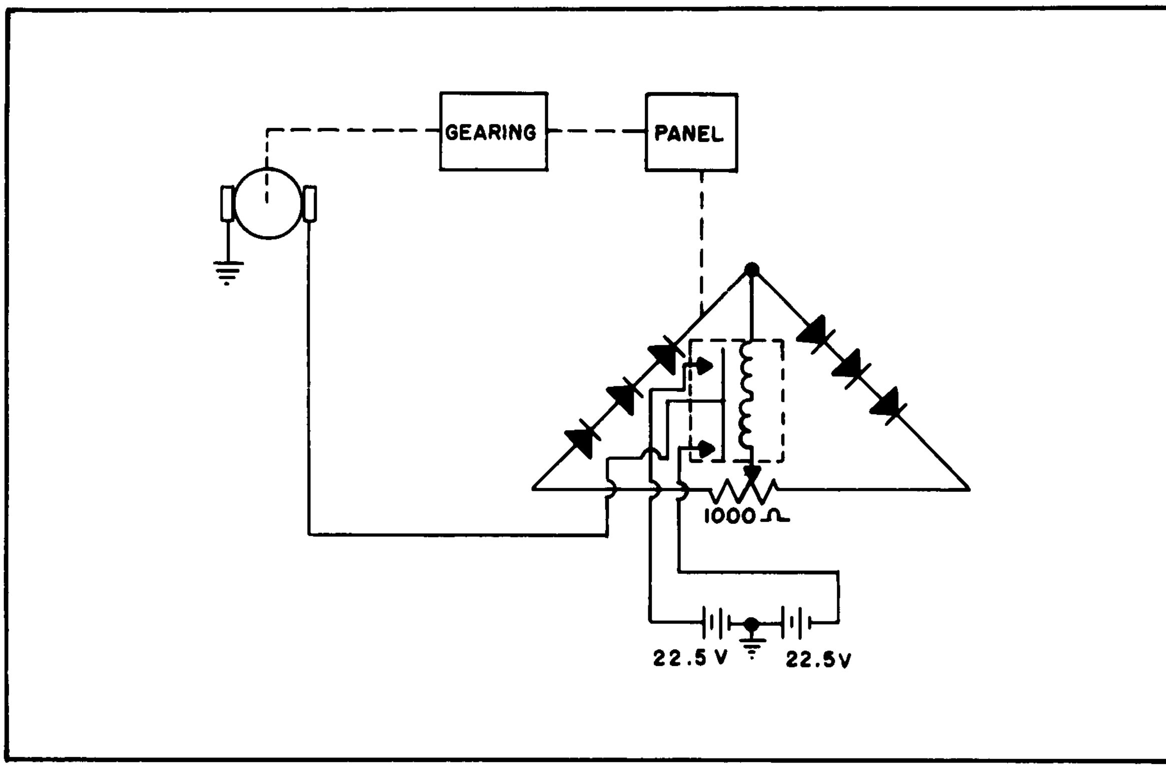

Figure 17 - Orientation Sensor Circuit Diagram

The pointing accuracy of the sun sensor and array was determined (during the outdoor test) by noting the length of shadow produced on the face of the sensor by the shade as outlined in Section I. The pointing accuracy of the array was within ±5 degrees.

Using the same battery, an indoor test was performed to determine the amount of power drain for a 360-degree rotation of the simulated array. The power drain on the battery was about 3 watts (250 milliamperes), and 545 seconds were required for the complete rotation of the array. The energy consumed was 0.454 watt-hours.

PART 5 - CONCLUSIONS

A shade (plate extending beyond the actual apex of the sensor) should be used with the sun sensor to increase its sensitivity near the null point. The length of the shade is given by

$$b = \frac{X \sin(\beta - \alpha)}{\sin \alpha}$$

where

X = the distance along one of the faces of the sensor (measuring from the sensor apex to the edge of the shadow produced by the shade)

β = the value of one half the included apex angle

α = the angle between the sun direction and sensor direction.

The sun's declination is changing with time and its value can be predicted accurately using the ephemeris. A mean value of the solar declination can be used for a constant setting of the array, so that with an hour angle drive error of 6 degrees and a permissible declination change of 8 degrees, a total of 42 days of unattended operation can be achieved as pointed out in the example given in Section II.

The sun sensor should be located so that its base is 4 inches above the center of the upper edge of the array for the 25 square-foot size and 2-1/2 inches for the 10 square-foot array. This is to prevent the shadow produced by the edge of the array from falling on the cells of the sensor. It should be noted that these values are for square arrays and allow a declination change up to 7 degrees.

The array tracking rate may be expressed by the equation

$$\dot{\alpha} = \frac{\dot{P}_A}{P_{max} \sin \psi} - \dot{\theta}$$

where

$\dot{P}_A$ = the rate of change of output power from the array as it moves toward normal incidence with the sun

P_{max} = the maximum power from the array when it is in normal incidence with the sun's radiation

ψ = the angle between the sun's direction and the normal to the array

$\dot{\theta}$ = the apparent angular motion of the sun.

The present sun sensor is designed for single-axis operation, and a modification would be required to sense the sun's declination change. A sensor in the shape of a solid pyramid with a square base may be utilized. Two faces of the pyramid would contain the cells for sensing the error in hour angle drive, and the other two faces would sense the error due to declination change. The shade, which was a vane in the previous sensor, will have the shape of a solid rectangular block and will be used for each face of the pyramid.

The additional hardware for implementing the two-axis approach would consist of a micropositioner, revised sun sensor, another d-c drive motor with gearing, and the necessary mechanical linkage. Some extra electrical power is required for the declination drive, but since the duty cycle for this portion of the system is small, the power drain should be relatively small also.

The following expression relates the height (H) from the ground to the array attachment point with the leg length and the total weight to wind force ratio:

$$H = Z + h = \frac{L}{2}\sqrt{\left(\frac{W}{F}\right)^2 - 1}$$

where

Z = distance from ground to top leg attachment point

h = distance to avoid interference from legs

L = leg length measured in horizontal plane

W = total weight (mount plus array)

F = resultant wind force (wind pressure times effective array area).

Consideration should be given to the latitude regions of operation. Restriction to certain latitudes of operation may permit a decrease in the distance (h) and a corresponding lower center of gravity.

Equipments required for setting up the array are a circular bubble level attached to the mount, which is used to obtain an initial leveling of the mount, a latitude dial for the establishment of the correct polar axis, and a declination dial for setting the proper mean value of the declination into the mount. These dials can be obtained to an accuracy of six minutes of arc. A compass and map of the area in which operation is to be conducted may be used to obtain the north-south alignment of the mount. A card can be prepared for reading the proper declination to set the mount.

The breadboard model of the mount, drive unit, and sensor was tested on 26 December 1961 and operated within the accuracy specification. A 45-volt, center-tapped "B" battery (EVEREADY No. 762-S) was used for power to the drive motor. Power drain on the battery was about three watts, and 545

seconds were required for a 360 degree rotation. Energy consumed would be 0.454 watt-hour.

PART 6 - PROGRAM FOR NEXT PERIOD

The program for the next period will consist of the following:

1. Complete fabrication of the orientation sensor (this has not been completed due to the delay in delivery of solar cells) and testing to evaluate drift, null zone, and sensitivity.
2. Continue testing with the breadboard model of the mount, drive unit, and sensor.
3. Complete final mount design based on experimental and analytical results.
4. Extend the mount design parameters to accommodate the latest figures of the 100-watt solar array, which are 36 square feet and a weight of 85 pounds.

PART 7 - MANHOUR BREAKDOWN

Table II lists the manhour totals for the second quarter.

TABLE II - MANHOUR BREAKDOWN FOR SECOND QUARTER

Personnel		Manhours			
Name	Title	Oct	Nov	Dec	Total
McKeel, G. J.	Project Engineer	44.7	68.0	110.5	223.2
Loughridge, R. H.	Development Engineer	133.0	83.0	30.0	246.0
Steiner, W. L.	Support Engineering	0	4.0	0	4.0
	Subtotals	177.7	155.0	140.5	473.2
Total for Engineering Shop, Lab, and Presentations					276.5
	Total				749.7

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Unclassified report

Orientation sensor analysis is extended to yield a formula for determining the sensor pointing accuracy. The effect of solar declination change on the total angular error of the array and the position for mounting the sensor are covered. Requirements for automatic declination control are examined, and a feasible approach to the orientation sensor is given along with the circuit diagram. A mount analysis is presented to investigate the effects of total height, leg length, and overturning forces. Setting up the mount for outdoor conditions is discussed, relating some of the necessary equipment. Experimental results gained during the period from the breadboard model of the mount, drive unit, and sensor are given.

UNCLASSIFIED

1. Orientation sensor analysis including shade attachment.
2. Solar declination effects on total angular error and sensor position.
3. Automatic declination control requirements.
4. Mount analysis and setup procedure.
5. Experimental results with breadboard model of mount, sensor, and tracking drive.

I. Solar Orienting Device
II. McKeel, G. J.
III. U.S. Army Signal R&D Lab, Ft. Monmouth, N.J.
IV. Contract DA36-039-SC-88913.

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